PLANETARY POLARIZATION NEPHELOMETER

D. Banfield[(1)], M. Roos-Serote[(2)], D. Stam[(3)], H. Volten[(3)], O. Munoz[(4)], M. Mishchenko[(5)], R. Dissly[(6)], P. Gierasch[(1)]

[(1)]Cornell Astronomy, 420 Space Sciences, Cornell University, Ithaca, NY, 14853), Email:banfield@astro.cornell.edu
[(2)]Presenting Author, Lisbon Astronomical Observatory, Lisbon, Portugal
[(3)]Astronomical Institute "Anton Pannekoek", University of Amsterdam, The Netherlands
[(4)]Institute for Astrophysics of Andalucia, Granada, Spain
[(5)]NASA GISS, New York, NY, USA
[(6)]Ball Aerospace and Technology Corp., Boulder, CO, USA

ABSTRACT

We are developing a polarization nephelometer for use on future planetary descent probes. Significantly exceeding the capabilities of previous planetary nephelometers, it will measure both the scattered intensity and polarization phase functions of the aerosols it encounters descending through an atmosphere. These measurements will be taken at two wavelengths separated by about an octave (e.g., 1μm and 500nm). Adding polarization measurements to the intensity phase functions *greatly* increases our ability to constrain the size distribution, shape and especially the chemical composition of the sampled particles. There remain important questions about these parameters of the aerosols on Venus, the giant planets and Titan that can only be addressed with a polarization nephelometer like ours. The NRC Planetary Sciences Decadal Survey has identified probe missions to Venus and Jupiter as a priority. On both of these missions, our proposed instrument would be an excellent candidate for flight. We also expect that future probe missions to Saturn, Uranus, Neptune and Titan would employ our instrument. It could also find use in Earth and Mars *in situ* aerosol studies.

We use a technique to simultaneously measure intensity and polarization phase functions via polarization modulation of a light source. A similar technique has been implemented in laboratory settings, but not with considerations to the environment on a planetary descent probe. We are designing and building a flexible breadboard nephelometer to verify our approach and candidate components. We will test it against well defined aerosols and other simple scatterers ensuring that it accurately measures their expected intensity and polarization phase functions. With the knowledge gained in this flexible design, we will design and build a breadboard polarization nephelometer more suited to integration on a planetary descent probe. All of these investigations are being carried out to enhance the likelihood of success and useful data return of our proposed instrument in its descent through a planetary atmosphere. Considerations will also be given to mass, volume, power and cost.

1. Introduction

1.1 Aerosols: Key Observations

The aerosols that reside in the atmospheres of Venus, the giant planets and Titan are the visible faces of these planets, and yet we have quite limited knowledge of them. The impact of this lack of knowledge is significant on our understanding of the composition, structure and dynamics of these planetary atmospheres. We directly address this with our proposed polarizing nephelometer. Our discussion of the scientific relevance of a nephelometer is divided into Venus and Jupiter reasons. However, most of the Jupiter arguments raised apply equally well to the other giant planets and Titan. This means that a broad variety of descent probe mission scenarios could benefit from our instrument, from Discovery to New Frontiers.

1.2 Venus

For Venus, we have some detailed knowledge of the cloud layers from remote sensing and also from earlier nephelometers placed in Venus' atmosphere on Russian and American probes. These studies, crudely summarized, have told us that the Venus atmosphere has 3 main cloud decks, extending from about 45km to 70km, with hazes both above, below and between these layers (e.g., [1,2,3]). The optical thickness of the top-most cloud is dominated by 1μm spherical aerosols of concentrated sulfuric acid[4]. There are large opacity variations in the middle and lower cloud decks (e.g., [5]). But in spite of this detailed knowledge of the clouds on Venus, there are still significant questions that can be answered with a nephelometer at Venus.

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As a basis for this discussion, we take the goals outlined in the NRC Solar System Exploration Decadal Survey's chapter, “The Case for Venus Exploration.” The first topic identified there for which a nephelometer is crucial is the trace gases in Venus' atmosphere. These include sulfur, which plays a key role both in the clouds (via H_2SO_4), and the surface-atmosphere interactions (via volcanic injection and/or surface chemical weathering). If a probe only measured the gas phase abundances of sulfur bearing molecules it would exclude a significant reservoir, namely the aerosols. In the clouds, roughly 1/3 of the sulfur may be in aerosols. Our proposed nephelometer could yield these abundances, completing the trace gas inventories produced by a Venus probe. Furthermore, the debate still continues whether a crystalline “mode 3” family of particles exists in the middle and lower clouds. If these are a distinct material from H_2SO_4, then they represent a significant reservoir of unknown material, and must be accounted for in chemical/aerosol models of the atmosphere. Our proposed instrument could well determine the size, shape and index of refraction of the aerosols in Venus' atmosphere leaving little ambiguity, and thus clarifying these outstanding questions.

The second topic concerns the greenhouse effect on Venus. Current greenhouse models still leave open debates about the relative importance of various contributors to the observed temperature on Venus. The clouds represent a substantial absorber of solar and thermal energy on Venus, and defining their microphysical properties and vertical structure is critical in fully understanding the mechanisms that control the greenhouse. A prime example is that the upper cloud has a still unknown blue absorber which is responsible for about 1/4 of all solar energy absorbed by Venus. Identifying this absorber is a task that our proposed polarizing nephelometer would be ideally suited to. Specifying the upper cloud particles' shapes and indices of refraction (for the different modes) may unlock the puzzle of this climatically important blue absorber. Tying back into the previous topic, once this blue absorber is identified, understanding its chemical origin from the trace gases, and the connection with surface processes will be very interesting. Ref. [6] have suggested that the blue absorber may be sulfur allotropes, identifiable by their influence on the index of refraction of the aerosols. In this way, Venus may be a proxy for the early Earth. Recent work suggests Earth's early oxygen abundances were so low as to favor SO_2 photolysis proceeding to sulfur allotropes. Producing better constraints on the blue absorber, and possible sulfur allotropes on Venus will add to our understanding of both Venus and early Earth.

The third topic addressed in the decadal survey is the middle atmosphere composition. Chemical cycles between CO_2, CO, O, O_2 are believed to be catalyzed towards CO_2 by heterogeneous chemistry involving sulfur or chlorine molecules. Without this heterogeneous chemistry cycle, the bulk constituent of Venus' atmosphere, CO_2, would rather be in the form of CO and O_2. Once again, understanding the aerosol profiles, and their coupling with the trace gases is key to fully understanding this important atmospheric chemistry cycle. Correlating the (gas phase) trace gas profiles with the aerosol profiles is critical to *fully* understanding the chemistry. Remote sensing observations from orbit will not allow detailed enough specification of the variable aerosol environment to fully understand the observations. The UV contrast on Venus is likely tied to processes where local flows alter both the trace gas abundances and the aerosols. In that sense, this question boils down to one as fundamental as understanding the visible appearance of Venus, in addition to the core questions about the stability of the atmospheric composition.

Other factors to consider that are not specifically called out in the decadal survey include aerosol-dynamic feedbacks and their influence on local trace gas abundances. Nightside near-IR contrast variations suggest that small scale convection patterns occur in the lower cloud while the middle cloud has a global scale (m=1) pattern of cloud opacity variation. The heating caused by these opacity variations is enough to locally influence the buoyancy and circulation, perhaps suggesting a feedback between flow and aerosol opacity. The possibility exists that such feedbacks may be important in controlling the local profiles of trace gases, especially those that have significant vertical variations in the vicinity of the clouds. Obtaining gas phase abundance measurements without placing them in the context of the local heating environment (and thus the local vertical flow) could lead to inaccurate assessments of atmospheric chemical cycles. Thermal structure and accelerometer measurements alone will not reveal the vertical winds that the probe moves through. Measuring the aerosol density is one approach to infer these effects on the rest of the descent probe's observations. Another practical matter involves identifying precisely when an observation from (e.g.) a mass spectrometer may have ingested an aerosol drop, skewing its results. Without a direct measure of the aerosol density, this will leave an ambiguity in the interpretation of gas phase measurements.

The above arguments show why, scientifically, a nephelometer is a critical part of Venus probe missions. Three of the scientific goals above are identified specifically in the decadal survey's report on observation priorities for Venus. They all address questions relating to the composition of Venus' atmosphere, the surface-atmosphere interaction, or most directly the geochemical cycles affecting the climate of Venus.

1.3 Jupiter

For Jupiter, we know even less about the clouds than for Venus. The one descent probe that entered Jupiter's atmosphere, Galileo's probe, entered into an anomalous hotspot location (e.g., [7]). It is generally not believed that the Galileo probe's findings are representative of the cloud structure of a generic region on Jupiter. Remote sensing has revealed significant facts about Jupiter's clouds, but important ambiguities still remain (e.g., [8]). An example of this is that we do not know the vertical structure of the clouds on Jupiter. For instance, the contrast-bearing cloud deck may be composed of either ammonia or ammonium hydrosulfide aerosols. Remote sensing studies have been unable to agree on this point, with visible wavelengths tending to support ammonia clouds bearing the contrast (e.g., [9]), and near-infrared wavelengths indicating ammonium hydrosulfide (e.g., [10]). A side effect of this remote sensing ambiguity is that when we measure cloud-tracked winds on Jupiter, we do not know what level (or levels) they represent. This significant hole in our understanding has propagating effects into dynamical models, limiting their ability to fully understand the driving circulations of Jupiter. A nephelometer on a Jupiter descent probe, entering a representative region of the planet would easily clarify the vertical structure of Jupiter's clouds.

It may turn out that Jupiter's clouds are a more complex mixture of aerosols of water, ammonia and ammonium hydrosulfide than our simple models have suggested. There are several indicators that water vapor is advected up above the top cloud deck[9, 11]. This certainly raises the issue of how mixed the cloud species are on Jupiter. measurement of the optical properties of the aerosols with our proposed nephelometer can yield not only the vertical structure and thicknesses of the clouds, but also some leverage into identifying their chemical abundances.

The deep water abundance of Jupiter, a key quantity in helping to understand the formational scenarios of the giant planets, can also be estimated from the pressure of the water cloud base. While mass spectrometers are an ideal way to estimate this quantity, corroborating evidence from the condensational behavior of water, documented by our proposed nephelometer can help alleviate ambiguities that might arise from contaminated intakes on the relatively complicated mass spectrometers.

If we have the luxury of deploying several entry probes into an atmosphere, spatial perturbations in the cloud structure are indicative of the atmospheric motions. An extreme example of this was the Galileo probe's nearly completely clear atmosphere, which indicated a strong downdraft in the vicinity of the hotspot that it entered. A more representative location may still have some modest vertical winds, which can be inferred by comparing with neighboring probe results. This type of study can greatly add to our full understanding of the dynamics of the giant planet atmospheres.

Another example where nephelometers have significant value addresses the fact that we don't understand what provides the colors of Jupiter. Studies suggest it is blue absorbers located in the upper troposphere[8,12], and that there are probably at least 2 different coloring agents[13]. Beyond this, little is known about these absorbers. Our proposed instrument should be able to identify the real and imaginary parts of the index of refraction of the aerosols at two different wavelengths. This should give significant leverage in identifying these chromophores. Presumably identifying the chromophores will also have impacts on the photochemical/aerosol models of Jupiter's stratosphere and upper troposphere.

Finally, documenting the aerosol size distributions more carefully, as we could do with our proposed nephelometer, would allow a more accurate assessment of the thermal and radiative balance at varying levels in the giant planet atmospheres to be determined. The thermal infrared flux that is capable of escaping the atmosphere from the layers below the visible cloud deck is poorly constrained, and important for understanding the dynamics in the layers just below the visible cloud deck. There are hints from the water vapor cumulus towers that the dynamics in this region (1-6 bars) might be pivotal in controlling the “weather” on Jupiter. For us to fully understand the role that radiation and convection play in transporting heat through this region, the aerosols need to be well quantified, not only in number density versus pressure level, but also size distribution, shape and albedo. Our proposed nephelometer is the ideal instrument to characterize the aerosols in all these dimensions.

The majority of these areas in which a nephelometer could expand our understanding of Jupiter's atmosphere were specifically called out in the "Decadal Survey." Specifically, the survey's Planetary Atmospheres chapter identifies the measurement of horizontal and vertical variability of aerosols, and scattering properties of the condensed particulates. It also lists needs more indirectly addressed by nephelometer observations including the role of the latent heat of water in Jovian dynamics, deep H abundance, and horizontal winds over several scale heights.

It should be noted that many of the arguments listed above for a nephelometer at Jupiter apply equally well to the other giant planets and some also apply to Titan. In fact, the "Decadal Survey" calls out the need for a multiple probes to Neptune, each equipped with a nephelometer. For Earth and Mars, this instrument may find important applications. Commercial applications on Earth include non-contact testing of exhaust gases from both internal combustion and turbine engines. Balloon-borne investigations with this nephelometer would prove interesting for both Earth and Mars. To carefully study the aerosols on Mars (and by extension, their electrostatic and optical effects), we could place this nephelometer on a lander or rover to study the aerosols that pervade the operational environment on the Martian surface.

2. NEED FOR UPDATED APPROACH

2.1 Modernization

The most recently built planetary descent probe nephelometer was that for the Galileo Probe, designed in the late 1970's. It weighed 4.4kg and used 11W[14]. Modern opto-electronics have advanced considerably since then, with better detectors, semiconductor lasers, and high temperature fiber optics as well as all the advances in electronics miniaturization. Mass, volume and power are all precious commodities on an entry probe, and these can certainly be trimmed using modern electro-optic approaches to a nephelometer.

Nephelometers designed for use in the Earth's atmosphere have taken advantage of the optoelectronic advances since the Galileo design. Our approach is similar to that of [15], and especially that of [16]. In both of these cases, semiconductor lasers are used as the light sources, fiber optics are used to collect the scattered light, and photodiodes are used as detectors. We will employ all of these techniques in our design. However, because mass and volume and reliability are given such a premium on planetary instruments, our instrument will differ from those used in the earth's atmosphere. Additionally, the nature of the aerosols encountered on the other planets is much less well known (as fundamental as molecular composition), demanding more information content from our instrument than that which is sufficient for Earth aerosol studies.

2.2 Augmented Capabilities

Our proposed nephelometer will measure both the scattered intensity and polarization ratio at several angles from near backscatter to near forward scatter from aerosols it encounters on descending through a planetary atmosphere. It will perform these measurements at two wavelengths separated by about an octave, with one laser near 500nm and another near 1μm.

Traditionally, a simple nephelometer measures at least the backscatter intensity as an indicator of the backscatter coefficient (roughly speaking, the cloud density) of the aerosols in its vicinity. Some nephelometers (e.g., the Galileo Probe nephelometer) also measure the intensity of the scattered radiation with varying scattering angle. Adding this intensity phase function information gives some information on the particle size, shape and indices of refraction. However, typically these parameters can not uniquely be extracted from the intensity phase function alone, and results are quite model dependent. By also measuring the polarization phase function, we can have a drastically improved metric with which to infer the particle microphysical properties. We can retrieve much more tightly constrained particle size and refractive indices fitting this expanded data set (e.g., [17]).

To further augment the information content returned by our instrument, we intend to measure the intensity and polarization phase functions at two wavelengths separated by about an octave. These functions at only one wavelength allow a good inference of the particle properties under assumptions about the simplicity of their size distribution. Adding information at a second wavelength, which samples the aerosols with a size parameter different by about a factor of two, introduces more robustness into the retrievals in the presence of broader aerosol size distributions. For example, the diffraction feature probed by forward-scattering angles can be expected to change quite significantly with a factor-of-two change in the particle size parameter, which provides an additional constraint on the cloud-particle size distribution. Furthermore, differences in the indices of refraction for the aerosols at the two wavelengths examined can be a strong discriminator for the composition of the aerosols, as was demonstrated by [4]. We have chosen roughly 0.5μm and 1μm mainly for the range in particle size parameter this achieves and also for the availability of reliable laser sources and receiving optics at these wavelengths. Additionally, it is well known that measurements of light scattering are most sensitive to particle microphysics when the wavelength is comparable to the size (e.g., [18]), so the expected aerosol sizes in planetary atmospheres (0.1μm to 10μm) will be well resolved with laser light at these wavelengths.

3. PRINCIPLES OF POLARIZATION MODULATION

Our polarization nephelometer conceptual design is based on the technique described in [19](see sect. 13.7). Optimally, to extract the most information possible from light scattered from an aerosol, one should measure all elements of the scattering matrix as a function of scattering angle. The scattering matrix (a 4x4 matrix translating the incoming beam's 4-element Stokes vector into an outgoing Stokes vector) has only 6 unique elements for randomly oriented particles with a plane of symmetry. Of those 6 elements, the most important information is contained in the S_{11} function, essentially the intensity phase function, and the S_{12}/S_{11} function, essentially the polarization phase function (e.g., [20, 18]). Ref. [21] first demonstrated a technique by which these elements of the scattering matrix could be obtained simultaneously from time resolved measurements of the scattered light illuminated by a polarization modulated source. With the correct sequence of static polarizers, quarter wave plates and polarization modulators, any of the scattering matrix elements can be extracted from the time resolved scattered signal. The intensity and polarization ratio are particularly simple to observe, needing no other optical elements than the polarization modulated source. In this case, the intensity phase function will be the DC component of the scattered signal, while the polarization ratio is the amplitude of the signal at the modulation frequency. This is precisely the approach that we plan to take.

In its complete form, this approach has already been successfully implemented in laboratory settings. Hunt and co-workers have been using this technique since the 70's, with recent work directed at characterizing laboratory-proxy marine aerosols ([22]) and diesel exhaust aerosols ([23]). The Russian literature also shows evidence of similar instruments for quite some time (e.g., [24]). Our team members in the Netherlands and Spain have also built laboratory equipment using this technique to characterize aerosol scattering matrices (e.g., [25, 26]).

In the Russian instruments, the polarization modulation is achieved by means of a rotating mica (birefringent) crystal ([24]). This mechanical approach to the modulation is undesirable for a flight instrument due to the inherent risks. In the instruments built by [23], a Pockels cell is used to modulate the polarization state of the incident light. A Pockels cell is a birefringent crystal which can have its optical path length modified via acoustic forcing (e.g., from a tuned piezo crystal clamped to one end of the birefringent crystal), thus introducing a precise (but varying) phase shift between the orthogonal polarizations of an incoming beam. To allow the separation of the scattering matrix elements from one another, the amplitude of the polarization modulation must be very precisely controlled. While this is feasible in a laboratory setting, these devices are quite sensitive and would prove very unstable in a planetary descent probe environment. The most obvious sensitivity is due to thermal expansion. The precise phase difference produced by the polarization modulator is a function of its dimension along the optic axis. Most polarization modulators are multi-order retarders, where the phase shift induced over the path through the device is $n2\pi + \phi$ where the $n2\pi$ has no net effect, but is required for manufacturing and strength considerations for the material used. A small fractional change in length of the material along the optic axis then means a similar small change in $n2\pi + \phi$, which will result in a large fractional change in the (significant) ϕ. In addition to temperature changing the thickness of the component, it can also change its birefringence. Typically, this is an effect on the order of 0.02%, which can again mean large fractional errors in the significant phase shift for multi-order retarders. Similarly, if the wavelength of the source beam changes (for whatever reason), the multi-order retarders again sensitively change their effective phase shift by large amounts. All of these problems mean that the (relatively) poorly controlled thermal environment of a planetary descent probe is an unwise location to deploy an instrument using a Pockels cell.

Instead, our proposed technique does not use a polarization modulator at all, but rather modulates between two orthogonally polarized lasers. There are no other polarizing elements in the system aside from the scatterers themselves. The detector is polarization insensitive, yet the two scattering matrix elements can be retrieved from the DC and time varying components of the received intensity, similar to the terrestrial laboratory approach. This technique does not allow the flexibility to observe all 16 elements of the scattering matrix that the terrestrial lab technique does, but as argued above, the S_{11} and S_{12} elements are the most discriminating.

One assumption for our conceptual instrument above is that the detector is insensitive to polarization, which is not in general true for most detectors. However, to avoid the thermal environment external to a descent probe body, we will use fiber optics or light pipes to return the beam from various scattering angles to within the body of the probe. Not only does this provide for a much more stable (and thus well calibrated) environment for the detectors, it also should eliminate sensitivity to the incoming beam's polarization state. Fiber optics or light pipes of sufficient length are known to randomize the polarization state of a beam, thus rendering a detector at the far end of such a component insensitive to the polarization at the beginning.

4. DESIGN CONCEPT

As mentioned above, our proposed instrument is similar in design to that of [16], roughly 18cm across, using a semiconductor laser (4 in our case) for the source, fiber optics to collect the scattered light, and photodiodes to detect the light. In our case, the fiber optics not only allow sampling the scattering with fine angular resolution, but also the placement of the detector within the body of the probe, where the thermal environment can be much more carefully controlled. In fact, the source lasers, the photodiodes and blocking filters (to exclude most ambient background sunlight) will all be kept within the probe body and temperature controlled using peltier junctions. Given the thermal sensitivity of the detector and source elements in our design, it makes sense to design a system that is robust to the expected thermal environment from the outset. The thermal environment experienced by planetary probes can be extreme. This design places only lens and fiber elements in the ambient environment of the probe, and commercial versions of these elements that can withstand high temperatures are readily available.

Our device will sample the scattered light at many angles along one half of the azimuths (180°) of the scattering plane, from forward to side to backscattered light. We will also paint all surfaces of our test equipment (and eventually those of the probe) to minimize unwanted reflections. It will also have a beam trap in the forward scattering direction, but possibly differing from the configuration of [16]'s instrument, it will not initially have beam traps above and below the scattering plane. Rather, to minimize the weight of the device, we intend to design it to function fully open to the ambient environment, both with aerosols and light throughout. To avoid contamination from the ambient light, we will use narrow band filters to block most of the ambient light, yet match that of the source lasers, and also employ chopping (at a slower rate than the polarization modulation) to further remove the ambient light effects as was done by [16]. If we find that neither of these approaches are sufficient, we will fall back to the shrouded design concepts of [16] and [15]. This open volume concept constitutes one of the main design and test challenges of our effort. We strongly prefer not using a shroud as it reduces mass, complexity of accommodation on the probe, and concerns about flow distortion and condensation.

Because our sample volume isn't simply defined by an aerosol column width (as it would be for a shrouded design with a narrow column of aerosols), the sample volume of each detector will have to be defined by the source and detector beam widths. Similar to that done by [15], we will use hoods to limit the acceptance angle cones of the fiber optics. In the forward and backscattering directions, where the phase functions have the sharpest features, we will limit the angular extent of the detector fields of view to rather small angles (of order a few degrees), and in the sidescattering directions, where changes are more smooth, we will allow larger fields of view (e.g., 5-10 degrees). This choice will also offset the typical reduction in sidescattering efficiency relative to forward and backscattering, thus making all of the signals closer in absolute magnitude. This will make it easier to use the same detection devices for all angles sampled, yet still return the highest quality phase function information. The growth in the sidescattering fields of view will only be in the scattering plane. In the direction perpendicular to the scattering angle, we will always limit our acceptance angles to about 1 degree to avoid contamination of the polarization ratio signal in case this is an effect (e.g., oriented crystals).

For in flight calibration, as well as the early stage testing that we anticipate with our breadboard model, we plan to use an optical fiber as an infinite cylinder scatterer, as was done by [16]. This approach has the advantage of being extremely simple to setup, and yet has an analytical solution that is easily matched with the results. For the flight application, we expect that this could be maintained within the probe body, in the nominal scattering volume before the sensor arm is deployed out the edge of the probe body. At this time, before atmospheric entry, the scattered light from this well-known infinite cylinder could be recorded, then the sensor arm swung out to its deployed position to take real data. In the lab setting, with our breadboard model, the simplicity of a thin optical fiber as a calibration tool is again attractive. However, the optical fiber has the drawback that it is not particularly like the aerosols likely to be encountered in a planetary atmosphere. To better match the nature of the expected aerosols, we will use the simplest techniques that yield a well defined scattering result, nearly monodisperse water and polystyrene spheres. To produce the water spheres, we will use an ultrasonic vibrating orifice nebulizer, which typically produces spheres with a fractional size range of less than 0.3, various sizes for various openings. The polystyrene spheres can simply be purchased, but not in as small of sizes as we are likely to be able to produce water spheres. However, in the dry conditions of Boulder, we will have to consider evaporation of the water spheres (unless we can create a very humid environment in our testing area), demonstrating the relative merits of also using the polystyrene spheres.

5. RADIOMETRIC FEASIBILITY

The technical feasibility of our instrument concept can be demonstrated in two ways. First, the radiometric properties of our instrument are similar to that of the operational instrument of [15], although the geometry differs somewhat because of our application. Second, we can directly produce a radiometric model of the instrument and the scatterers it will be asked to characterize. By testing against realistic cases, we can verify the adequacy of our SNR for certain averaging lengths. Some extreme cases of the aerosols that might be measured include Jovian water clouds (the densest likely to be found in the solar system), and Venusian upper hazes (some of the thinnest). For the relatively stronger forward scattering, the scattered light is coupled into the detectors directly by the fibers. This provides samples closely spaced in angle. For weaker side scattering, the scattered light is collected by lenses before being fed to fibers, which in turn relay the signal to protected photodiodes. This provides more collected light at the cost of wider spacing in angle where the phase function changes less rapidly. These two modes of signal collection have a basis in the heritage established by [15].

We set the integration time at 1/20 of the residence time to assure that we compare signals from the same ensemble of particles for each polarization for each wavelength. Data from a large number of integrations are added to achieve adequate SNR. From the instrument parameters and an assumption of scattering at large values of the size parameter, we can calculate a total scattered power. From the power, our radiometric model estimates the SNR available for the preliminary instrument design. A useful way of presenting the SNR data is the measurement time required to achieve an SNR of 100.

For Jupiter water clouds there is no problem in obtaining large SNRs in a short measurement time ($<200\mu s$). The SNR is largely limited by Poisson statistics on the signal itself. For the Venus haze, the measurement is much more difficult. The SNR is limited by dark noise on the detector, so long averaging times are required (~100s). The differences between clouds and haze are not surprising. The cloud particles have a cross-sectional area 100 times the haze, and a number density 1000 times the haze. Even if detector dark current were not a problem, the haze would require a measurement time almost 1000 times that of the cloud from first principles. The dark noise makes the situation worse. Results for haze are not unreasonable. For example, a measurement time of 100s represents a vertical average of 1km, which is reasonable in a thin, hazy atmosphere. In 100s, the model predicts good data (SNR = 100 or more) for three of the six possible combinations of wavelength and angle. Some data of lower quality would be available for other combinations.

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